

1 Rainfall threshold calculation for debris flow early 2 warning in areas with scarcity of data

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9 **Abstract:** Debris flows are one of the natural disasters that frequently occur in mountain ar-
10 eas, usually accompanied by serious loss of lives and properties. One of the most used ap-
11 proaches to mitigate the risk associated to debris flows is the implementation of early warning
12 systems based on well calibrated rainfall thresholds. However, many mountainous areas have
13 little data regarding rainfall and hazards, especially in debris flow forming regions. Therefore,
14 the traditional statistical analysis method that determines the empirical relationship between
15 rainstorm and debris flow events cannot be effectively used to calculate reliable rainfall
16 threshold in these areas. After the severe Wenchuan earthquake, there were plenty of materi-
17 als deposited in the gullies which resulted in lots of debris flow events subsequently. The trig-
18 gering rainfall threshold has decreased obviously. To get a reliable and accurate rainfall
19 threshold and improve the accuracy of debris flow early warning, this paper developed a
20 quantitative method, which is suit for debris flow triggering mechanism in meizoseismal areas,
21 to identify rainfall threshold for debris flow early warning in areas with scarcity of data based
22 on the initiation mechanism of hydraulic-driven debris flow. First, we studied the characteris-
23 tics of the study area, including meteorology, hydrology, topography and physical characteris-
24 tics of the loose solid materials. Then, the rainfall threshold was calculated by the initiation
25 mechanism of the hydraulic debris flow. The results show that the proposed rainfall threshold
26 curve is a function of the antecedent precipitation index and 1-h rainfall. To test the proposed

27 method, we selected the Guojuanyan gully, a typical debris flow valley that during the
28 2008-2013 period experienced several debris flow events and that is located in the meizo-
29 seismic areas of Wenchuan earthquake, as a case study. We compared the calculated thresh-
30 old with observation data, showing that the accuracy of the method is satisfying and thus can
31 be used for debris flow early warning in areas with scarcity of data.

32 **Keywords:** Debris flow; rainfall threshold curve; rainfall threshold; areas with scarcity of
33 data

34 1 Introduction

35 Debris flow is rapid, gravity-induced mass movement consisting of a mixture of water,
36 sediment, wood and anthropogenic debris that propagate along channels incised on mountain
37 slopes and onto debris fans (Gregoretti et al., 2016). It has been reported in over 70 countries
38 in the world and often causes severe economic losses and human casualties, seriously
39 retarding social and economic development (Imaizumi et al., 2006; Tecca and Genevois, 2009;
40 Dahal et al., 2009; Liu et al., 2010; Cui et al., 2011; McCoy et al., 2012; Degetto et al., 2015;
41 Tiranti and Deangeli, 2015; Hu et al., 2016). Rainfall is an important component of debris
42 flows and is the most active factor when debris flows occur, which also determines the
43 temporal and spatial distribution characteristics of the hazards. As one of the important and
44 effective means of non-engineering disaster mitigation, much attention has been paid to
45 debris flow early warning by researchers (Pan et al., 2013; Guo et al., 2013; Zhou et al., 2014;
46 Wei et al., 2017). For rainstorm debris flows, the precipitation and intensity of rainfall are the
47 decisive factors of debris flow initiation, and a reasonable rainfall threshold target is essential
48 to ensuring the accuracy of debris flow early warning. However, if there are some extreme
49 events occurred, such as an earthquake, the rainfall threshold of debris flow may change.
50 Take the main earthquake-hit areas affected by the Wenchuan earthquake for example. In the
51 several years since the earthquake, intensive rainfall events have triggered massive debris
52 flows resulting in serious casualties and property loss, even in some of the gullies which have
53 never had debris flow before. For example, the Guojuanyang gully, a small gully located in the
54 meizoseismic areas of the big earthquake, has no debris flows under the annual-average
55 rainfall before 2008, but it became a debris flow gully after the earthquake under the same

56 ~~conditions, even the rainfall was smaller than the annual average rainfall. This indicates that~~
57 ~~earthquakes have a big influence on debris flow occurrence. The earthquake triggered many~~
58 ~~unstable slopes, collapses, and landslides, which have served as the source material for~~
59 ~~debris flow and shallow landslide in the years after the earthquake (Tang et al. 2009, 2012; Xu~~
60 ~~et al. 2012; Hu et al. 2014).~~ Therefore, the rainfall threshold of debris flow post-earthquake
61 is an important and urgent issue to study for debris flow early warning and mitigation.

62 As an important and effective means of disaster mitigation, debris flow early warning
63 have received much attention from researchers. The rainfall threshold is the core of the debris
64 flow early warning , on which have a great deal of researches yet (Cannon et al., 2008; Chen
65 and Huang 2010; Baum and Godt, 2010;Staley et al., 2013; Winter et al., 2013; Zhou and Tang,
66 2014; Segoni et al., 2015; Rosi et al 2015). Although the formation mechanism of debris flow
67 has been extensively studied, it is difficult to perform distributed physically based modeling
68 over large areas, mainly because the spatial variability of geotechnical parameters is very
69 difficult to assess (Tofani et al., 2017). Therefore, many researchers (Wilson and Joyko, 1997;
70 Campbell, 1975; Cheng et al., 1998) have had to determine the empirical relationship between
71 rainfall and debris flow events and to determine the rainfall threshold depending on the
72 combinations of rainfall parameters, such as antecedent rainfall, rainfall intensity, cumulative
73 rainfall, et al.. Takahashi (1978), Iverson (1989)and Cui (1991) predicted the formation of
74 debris flow based on studies of slope stability, hydrodynamic action and the influence of pore
75 water pressure on the formation process of debris flow. Caine (1980) first statistically
76 analyzed the empirical relationship between rainfall intensity and the duration of debris flows
77 and shallow landslides and proposed an exponential expression($I = 14.82D^{-0.39}$). Afterwards,
78 other researchers, such as Wieczorek (1987), Jison (1989), Hong et al. (2005), Dahal and
79 Hasegawa (2008), Guzzetti et al. (2008) and Saito et al. (2010), carried out further research
80 on the empirical relationship between rainfall intensity and the duration of debris flows,
81 established the empirical expression of rainfall intensity - duration ($I = D$) and proposed
82 debris flow prediction models. Shied and Chen (1995) established the critical condition of
83 debris flow based on the relationship between cumulative rainfall and rainfall intensity. Zhang
84 (2014) developed a model for debris flow forecasting based on the water-soil coupling
85 mechanism at the watershed scale. Tang et al. (2012) analyzed the critical rainfall of Beichuan



86 city and found that the cumulative rainfall triggering debris flow decreased by 14.8%-22.1%
87 when compared with the pre-earthquake period, and the critical hour rainfall decreased by
88 25.4%-31.6%. Chen et al. (2013) analyzed the pre- and post-earthquake critical rainfall for
89 debris flow of Xiaogangjian gully and found that the critical rainfall for debris flow in 2011 was
90 approximately 23% lower than the value during the pre-earthquake period. Other researches,
91 such as Chen et al. (2008) and Shied et al. (2009) has reached similar conclusions that the
92 post-earthquake critical rainfall for debris flow is markedly lower than that of the
93 pre-earthquake period. Zhenlei Wei et al. (2017) investigated a rainfall threshold method for
94 predicting the initiation of channelized debris flows in a small catchment, using field
95 measurements of rainfall and runoff data.

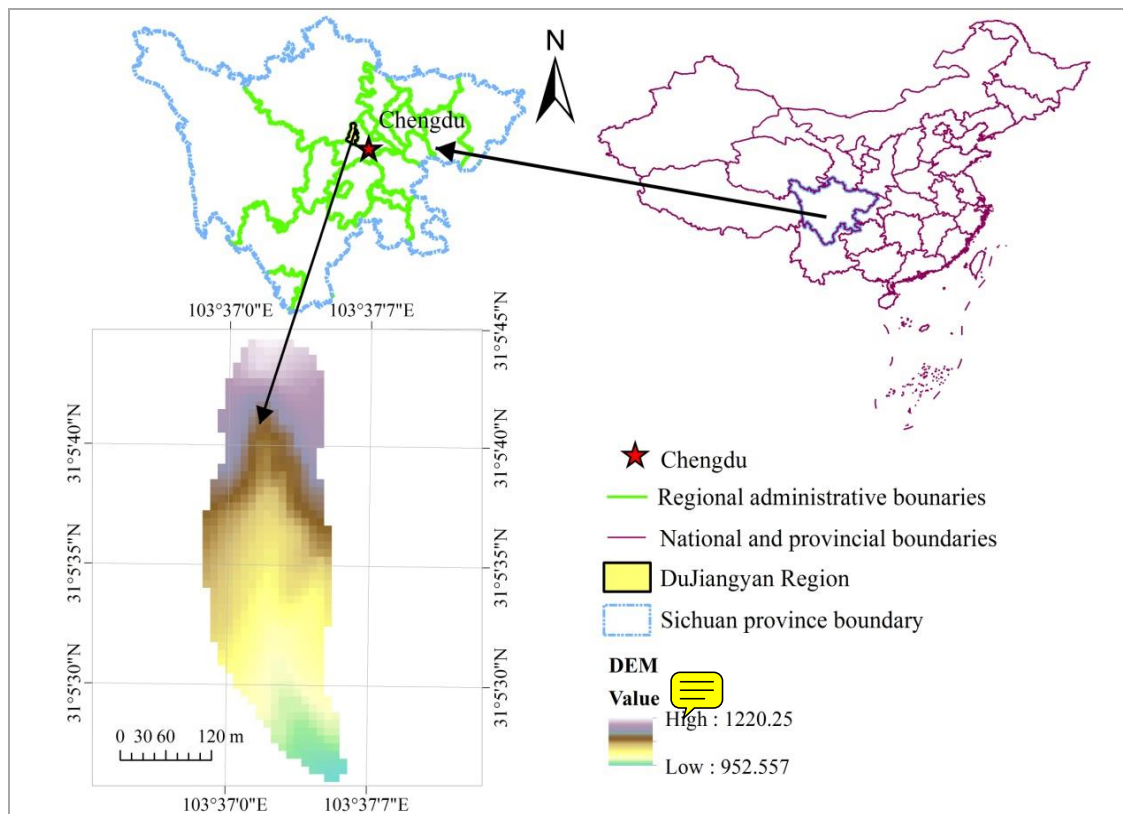
96 Overall, the studies on the rainfall threshold of debris flow can be summarized as two
97 methods: the demonstration method and the frequency calculated method. The
98 demonstration method employs statistical analysis of rainfall and debris flow data to study the
99 relationship between rainfall and debris flow events and to obtain the rainfall threshold curve
100 (Bai et al., 2008; Tian et al., 2008; Zhuang, et al., 2009). The I-D approaches would be this
101 kind of method. This method is relatively accurate, but it needs very rich, long-term rainfall
102 ~~sequence data~~ and disaster information; therefore, it can be applied only to areas with a
103 history of long-term observations, ~~such as Jiangjiagou, Yunnan, China, and Yakedake, Japan.~~
104 The frequency calculated method, assuming that debris flow and torrential rain have the same
105 frequency, and thus, debris flow rainfall threshold can be calculated based on the rainstorm
106 frequency in the mountain towns where have abundant rainfall data but lack of disaster data
107 (Yao, 1988; Liang and Yao, 2008). Researchers have also analyzed the relationship between
108 debris flow occurrences and precipitation and soil moisture content based on initial debris
109 flow conditions (Hu and Wang, 2003). However, this approach is rarely applied to the
110 determination of debris flow rainfall thresholds because it needs series of rainfall data. Pan et
111 al. (2013) calculated the threshold rainfall for debris flow pre-warning by calculating the
112 critical depth of debrisflow initiation combined with the amount and regulating factors of
113 runoff generation.

114 Most mountainous areas have little data regarding rainfall and hazards, especially in
115 Western China. ~~When a debris flow outbreak occurs, it often causes serious harm to villages,~~

116 ~~farmland, transport centers and water conservation facilities in the downstream area.~~ Neither
117 the traditional demonstration method nor frequency calculated method can satisfy the debris
118 flow early warning requirements in these areas. Therefore, how to calculate the rainfall
119 threshold in these data-poor areas has become one of the most important challenges for the
120 debris flow early warning systems. To solve this problem, this paper developed a quantitative
121 method of calculating rainfall threshold for debris flow early warning in areas with scarcity of
122 data based on the initiation mechanism of hydraulic-driven debris flows.

123 2 Study site

124 2.1 Location and gully characteristics of the study area



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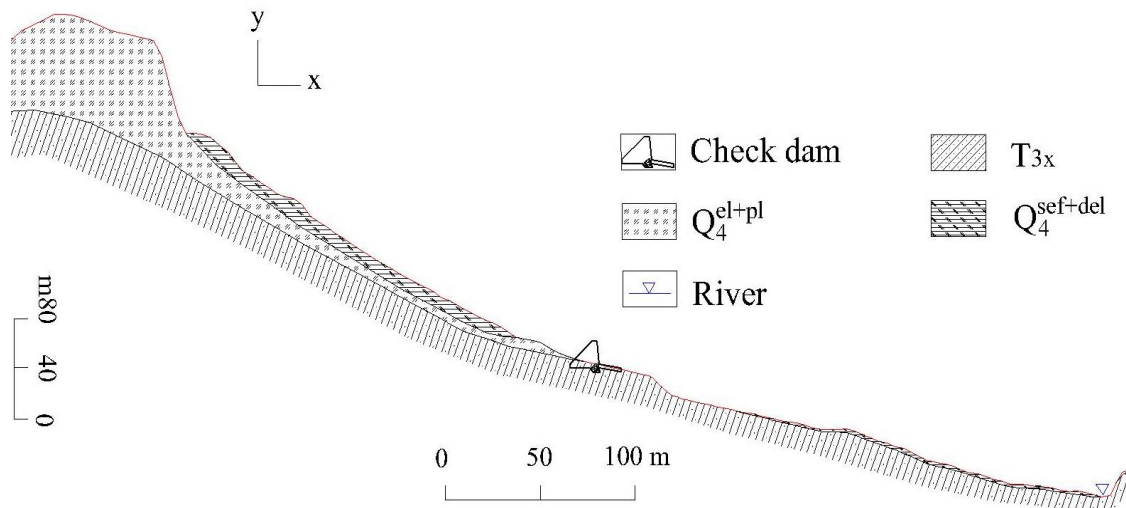
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Figure 1. The location of the Guojuanyan gully

127 The Guojuanyan gully in Du Jiangyan city, located in the meizoseismal areas of the
128 Wenchuan earthquake, China, was selected as the study area (Fig. 1). It is located at the
129 Baisha River, which is the first tributary of the Minjiang River. The seismic intensity of the
130 study area was XI, which was the maximum seismic intensity of the Wenchuan earthquake.

131 The Shenxi Gully Earthquake Site Park is at the right side of this gully. The area extends from
 132 $31^{\circ}05'27''$ N to $31^{\circ}05'46''$ N latitude and $103^{\circ}36'58''$ E to $103^{\circ}37'09''$ E longitude, covering an
 133 area of 0.15 km² with a population of 20 inhabitants. The elevation range is from 943 m to
 134 1222 m, the average gradient of the main channel is 270‰ (the average slope angle is 15.1°),
 135 and the length of the main channel is approximately 580m.

136 Geologically, the Guojuanyan gully is composed of bedrock and Quaternary strata. The
 137 bedrock is upper Triassic Xujiahe petrofabric (T_{3x}) whose lithology is mainly sandstone;
 138 mudstone; carbonaceous shale belonging to layered, massive structures; and semi solid-solid
 139 petrofabric. The Quaternary strata are alluvium (Q_4^{el+pl}), alluvial materials (Q_4^{pl+dl}), landslide
 140 accumulations and debris flow deposits ($Q_4^{sef+del}$). The thickness of the Quaternary strata
 141 ranges from 1 m to 20 m and varies greatly. The strata profile of the Guojuanyan gully is
 142 shown in Fig. 2.



143
 144 **Figure 2.** The strata profile of the Guojuanyan gully (Jun Wang et al, 2017)

145 Geomorphologically, the study area belongs to the Longmenshan Mountains. The famous
 146 Longmenshan tectonic belt has a significant effect on this region, especially the Hongkou-
 147 Yinxiu fault. The study area has strong tectonic movement and strong erosion, and the main
 148 channel is “V”-shaped. The area is characterized by a rugged topography, and the main slope
 149 gradient interval of the gully is 20° to 40°, accounting for 52.38% of the entire study area.

150 Climatically, this area has a subtropical and humid climate, with an average annual
 151 temperature of 15.2°C and an average annual rainfall of 1200 mm (Wang et al., 2014).

152 **2.2 Materials and debris flow characteristics of the study area**

153 The Wenchuan earthquake generated a landslide in the Guojuanyan gully, leading to an
 154 abundance of loose deposits that have served as the source materials for debris flows. A com-
 155 parison of the Guojuanyan gully before and after the Wenchuan earthquake is shown in Fig. 3.
 156 According to the field investigation and field tests, the landslide 3D characteristics induced by
 157 the earthquake and the infiltration characteristics of the loose materials are shown in Table 1
 158 and Table 2 (Wang et al., 2016). They indicate that the volume of materials is more than $20 \times$
 159 10^4 m^3 , and the infiltration capable of the earth surface have much increased. Therefore, the
 160 trigger rainfall for debris flow has decreased greatly. The Guojuanyan gully had no debris
 161 flows before the earthquake because of the lack of loose solid materials before the earthquake;
 162 however, it became a debris flow gully after the earthquake, and debris flows occurred in the
 163 following years (Table 3). The specific conditions of these debris flow events were collected
 164 through field investigations and interviews. The field investigations and experiments deter-
 165 mined that the density of the debris flow was between 1.8 and 2.1 g/cm³. Unfortunately, there
 166 were no rainfall data before 2011, when we started field surveys in the Guojuanyan gully.



167
 168 (a) 14 September, 2006 (b) 28 June, 2008

169 **Figure 3.** The Guojuanyan gully before (a) and after the Wenchuan earthquake (b) (from Google Earth)

170 **Table 1.** The landslide 3D characteristics induced by the earthquake in the study area

Average length /m	Average width /m	Average Height /m	Average depth /m	Slope /°	Volume / $\times 10^4 \text{ m}^3$
160	80	180	15	≥ 30	20

171

172 **Table 2.** The infiltration characteristics of solid materials in the study area

Infiltration curve	Infiltration rate	
	Initial infiltration /cm/min	Stable infiltration /cm/min
$f = 0.6529 \cdot \exp(-0.057 \cdot t)$	3.52	0.34

173 **Table 3.** The specific conditions of debris flow events in the Guojuanyan gully after the earthquake

Time	Volume (10 ⁴ m ³)	Surges	Rainfall data record
24 September, 2008	0.6	1	No
17 July, 2009	0.8	1	No
13 August, 2010	4.0	3	No
17 August, 2010	0.4	1	No
1 July, 2011	0.8	1	Yes
17 August, 2012	0.7	1	Yes
9 July, 2013	0.4	1	Yes
26 July, 2013	2.0	2	Yes
18 July, 2014	1.5	1	Yes

174

175 **2.3 Debris flow monitoring and streambed survey of the study area**

176 After the Wenchuan earthquake, continuous field surveillance was undertaken in the
 177 study area. A debris flow monitoring system was also established in the study area. To identify
 178 the debris flow events, this monitoring system recorded stream water depth, precipitation and
 179 real-time video of the gully (Fig. 4). The water depth was measured using an ultrasonic level
 180 meter, and precipitation was recorded by a self-registering rain gauge. The real-time video
 181 was recorded onto a data logger and transmitted to the monitoring center, located in the In-
 182 stitute of Mountain Hazards and Environment, Chinese Academy of Sciences. When a rain-
 183 storm or a debris flow event occurs, the realtime data, including rainfall data, video record,
 184 and water depth data, can be observed and queried directly in the remote client computer in
 185 the monitoring center. Fig. 5 shows images taken from the recorded video. These data can be
 186 used to analyze the rainfall or other characteristics, such as the 10-min, 1- and 24-h critical
 187 rainfall. The recorded video is usually used to analyse the whole inundated process of debris
 188 flow events and to identify debris flow events as well as the data from rainfall, flow depth, and
 189 field investigation.



(a) Real-time camera and rain gauge (b) Ultrasonic level meters

Figure 4. Debris flow monitoring system in the study area

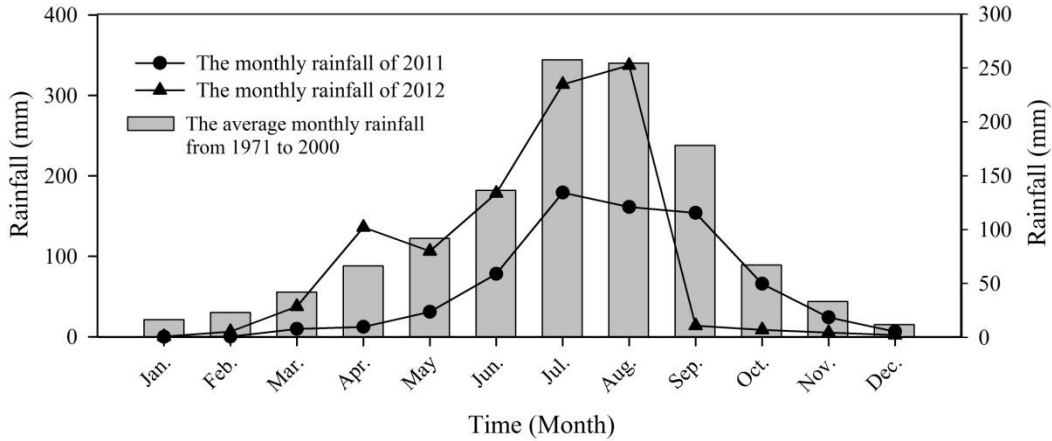


Figure 5. Real-time images from video taken during the debris flow movement

2.4 Data collection and the characteristics of rainfall

The Wenchuan earthquake occurred in the Longmenshan tectonic belt, located on the eastern edge of the Tibetan plateau, China, which is one of three rainstorm areas of Sichuan Province (Longmen mountain rainstorm area, Qingyi river rainstorm area and Daba mountain rainstorm area). Heavy rainstorms and extreme rainfall events occur frequently. Because there were few data in the mountain areas, we collected the rainfall data from 1971- 2000 and 2011-2012 (from our own on-site monitoring); the characteristics of the rainfalls are as following:

(1) Abundant precipitation: The average annual precipitation was 1177.3 mm from 1971 to 2000, and the average monthly precipitation is shown in Fig. 6. From 1971 to 2000, the minimum annual precipitation of 713.5 mm occurred in 1974, and the maximum annual precipitation of 1605.4 mm occurred in 1978. The total precipitation in 2012 is 1148mm, in the trend range of the historical data.

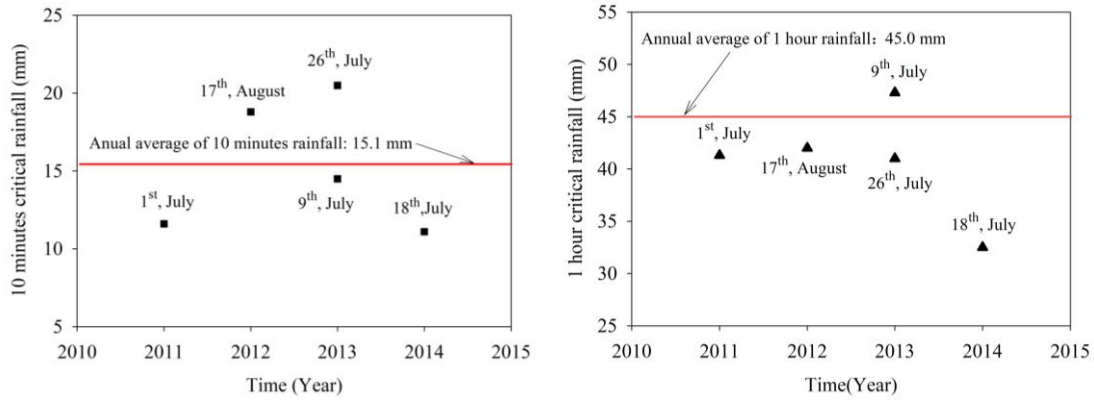


208
 209 **Figure 6.** The average monthly precipitation of the Guojuanyan gully from 1971 to 2000 and the
 210 monthly rainfall of 2011 and 2012

211 (2) ~~Severely inhomogeneous~~ distribution of precipitation ~~in time~~: from Fig. 6 we can ob-
 212 serve that rainfall is seasonal, with approximately 80% of the total rainfall occurring during
 213 the monsoon season (from June to September) and the other 20% in other seasons. And the
 214 laws of monthly rainfall in 2011 and 2012 coincide to the historical data. For instance, in 2012,
 215 the total annual rainfall in this area was approximately 1148 mm, and rainfall in the monsoon
 216 season from June to September was 961 mm, accounting for 83.7% of the annual total.

217 (3) ~~Due to the impact of the atmospheric environment, the regional and annual distribu-~~
 218 ~~tion of rainfall is seriously inhomogeneous; moreover, the rainfall intensity has great differ-~~
 219 ~~ences.~~ From 1971 to 2000, the maximum monthly rainfall was 592.9 mm, the daily maximum
 220 rainfall was 233.8 mm, the hourly maximum rainfall was 83.9 mm, the 10-min maximum
 221 rainfall was 28.3 mm, and the longest continuous rainfall time was 28 days.

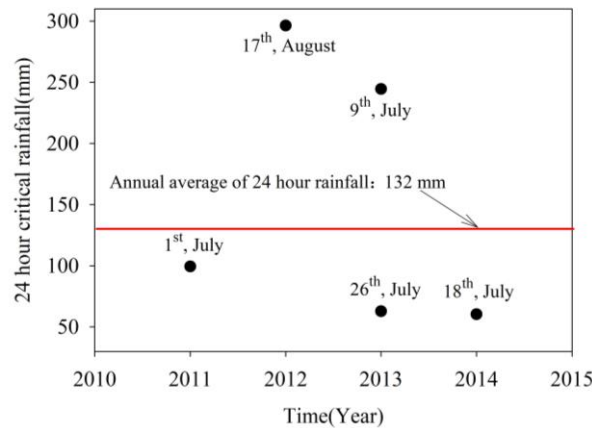
222 Debris flow field monitoring data and on-site investigation data were used to identify the
 223 debris flow events and to analyze the characteristics of the rainfall pattern and the critical
 224 rainfall characteristics. Analysing the typical rainfall process curves (Fig. 13), we can find that
 225 the hourly rainfall pattern of the Guojuanyang gully is the peak pattern, displaying the single
 226 peak and multipeak, a characteristic of short-duration rainstorms. Through the statistical
 227 analysis of the 10-min, 1-, and 24-h critical rainfall of debris flow events after the earthquake,
 228 their characteristics can be obtained, as shown in Fig. 7.



229

230

(a) The 10-min critical rainfall (b) The 1-h critical rainfall



231

232


(c) The 24-h critical rainfall


233

Figure 7. The critical rainfall of debris flows in the Guojuanyan gully

234

235 Fig. 7a shows that the observed 10-min critical rainfall is between 11.1 mm and 21.5 mm.
 236 According to the Sichuan Hydrology Record Handbook (Sichuan Water and Power Department
 237 1984), the annual average of maximum 10-min rainfall of the study area is approxi-
 238 mately 15.1 mm (from 1940-1975). According to the observation, 60% of debris flow events
 239 occurred below the annual average 10-min rainfall. In addition, the 1-h critical rainfall varied
 240 between 34.5 mm and 47.3 mm in the study area (Fig. 7b). And the annual average of maxi-
 241 mum 1-h rainfall is 45.0 mm (from 1940-1975) based on the Sichuan Hydrology Record
 242 Handbook (Sichuan Water and Power Department 1984). Figure 10b shows that 80% debris
 243 flow events occurred below the annual average 1-h rainfall, except for the debris flow event
 244 occurred on July 9, 2013. At last, the minimum value of 24-h critical rainfall is 60.4 mm and
 245 the maximum value is 296.4 mm in the study area. According to the Sichuan Hydrology Rec-
 ord Handbook (Sichuan Water and Power Department 1984), the annual average of maxi-

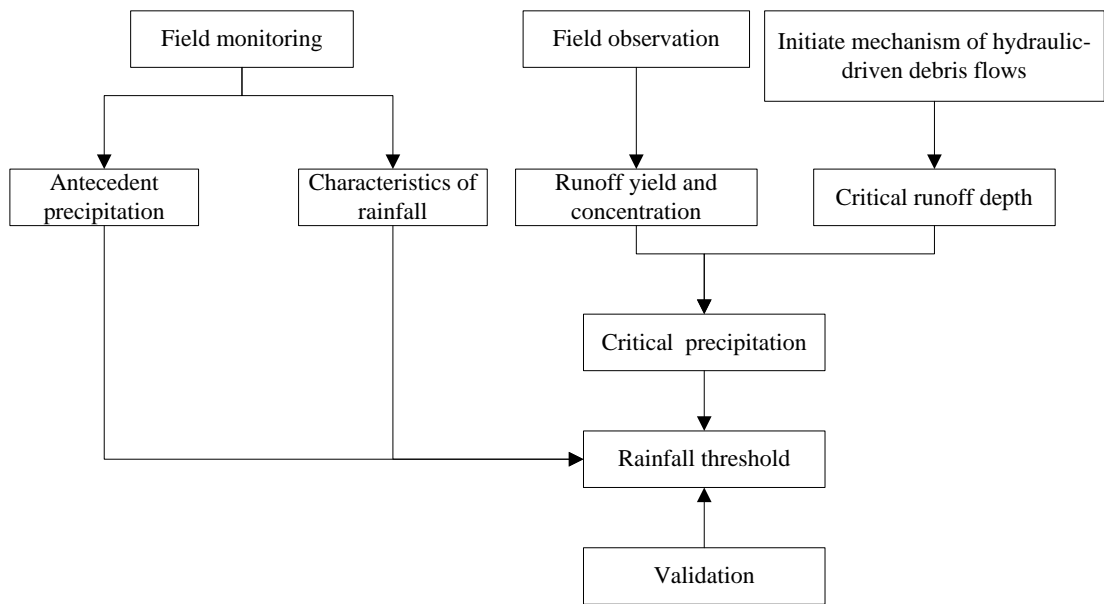
246 mum 24-h rainfall is 132 mm (from 1940-1975). From Fig. 7c, we can see that 24-h critical
247 rainfall for different debris flow events vary widely and 60% debris flow events occurred be-
248 low the annual average 24-h rainfall. 

249 From the above study, we can find that the 10-min and the 1-h critical rainfalls of
250 different debris flow events have minor differences; however, the 24-h critical rainfalls vary
251 widely. The reason is that debris flow is usually triggered by short-duration rainstorms.
252 Therefore, the short-durations of 10-min and 1-h rainfall have higher correlation with debris
253 flow occurrence and have the minor differences. **Actually, the 10-min rainfall intensity**
254 **(maximum precipitation over a 10-min period during the rainfall event) is the most**
255 **appropriate index for early warning of debris flow, which is most representative and has**
256 **minor error. However, it is difficult to obtain such short-duration rainfall data in actual debris**
257 **flow gullies because long-term rainfall monitoring system do not exist in most debris flow**
258 **basins especially in areas with scarcity of data. Further analyzing the 10-min and 1-h critical**
259 **rainfalls, we can find that they vary with the antecedent precipitation index (API). They are** 
260 **variable rather than constant.** In this paper, the antecedent precipitation index (API) and the
261 1-h rainfall (I_{60}) were used to calculate the rainfall threshold curve of debris flows in the
262 Guojuanyan gully.

263 **3 Materials and methods**

264 This study makes an attempt to analyze the trigger rainfall threshold for debris flow by
265 using the initiation mechanism of debris flow. Firstly, to analyze the rainfall characteristics of
266 the watershed by using the field monitoring data; then to calculate the runoff yield and con-
267 centration progress based on field observation. Additionally, the critical runoff depth to initi-
268 ate debris flow was calculated by the initiation mechanism with the underlying surface condi-
269 tion (materials, longitudinal slope, etc.) of the gully. Then, the corresponding rainfall for the
270 initiation of debris was back-calculated based on the stored- full runoff generation. At last,
271 these factors were combined to build the rainfall threshold model. This method can be applied
272 to the early warning system in the areas with scarcity of rainfall data.

273 The flow chart of the research is shown in Fig. 8.



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Figure 8. The flow chart of the research

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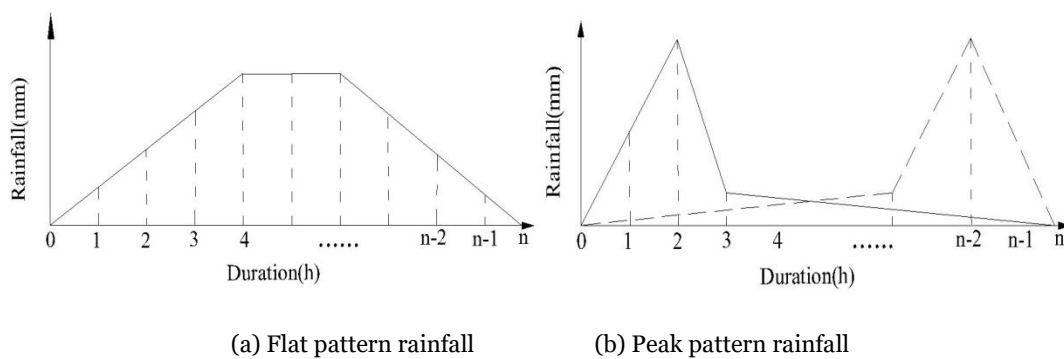
The main influence factors for the formation of debris flow event include three parts: a steep longitudinal slope of the gully (served as potential energy condition), abundant solid materials (source condition) and water source condition (usually is rainfall condition for rainstorm debris flow). For rainstorm debris flow events, the precipitation and intensity of rainfall are the decisive factors of debris flow initiation. Where if there is no earthquakes or other extreme events, the topography of the gully can be considered relatively stable. In contrast, rainfall conditions and the distribution of solid materials that determine the occurrence of debris flows can display temporal and spatial variation within the same watershed. Therefore, it is common to provide warning of debris flows based rainfall data after assessing the supply and distribution of loose solid materials. In Takahashi's model, the characteristics of soil, such as the porosity and the hydraulic conductivity of soils, are not considered, and considered the characteristic particle size and the volume concentration of sediment; while the characteristics of topography is mainly represented by the longitudinal slope of the gully. Furthermore, in the stored-full runoff model, the maximum storage capacity of watershed, which mainly decided by the porosity and permeability of the soil, may represent the characteristic of the hydraulic conductivity of solid material to a certain extent. Therefore, this study wouldn't consider the hydraulic conductivity any more.

294

3.1 Rainfall pattern and the spatial-temporal distribution characteristics

295 Mountain hazards such as debris flows are closely related to rainfall duration, rainfall
 296 amount and rainfall pattern (Liu et al., 2009). Rainfall pattern not only affects the formation
 297 of surface runoff but also affects the formation and development of debris flows. Different
 298 rainfall patterns result in different soil water contents; thus, the internal structure of the soil,
 299 stress conditions, shear resistance, slip resistance and removable thickness can vary. The ini-
 300 tiation of a debris flow is the result of both short-duration heavy rains and the antecedent
 301 rainfall (Cui et al., 2007; Guo et al., 2013). Many previous observational data have shown that
 302 the initiation of a debris flow often appears at a certain time that has a high correlation with
 303 the rainfall pattern (Rianna et al., 2014; Mohamad Ayob Mohamadi, 2015).

304 The precipitation characteristics not only affect the formation of runoff, also affect the
 305 formation and development of the debris flow. Different rainfalls result in different soil water
 306 contents, and thus the internal structure of the soil, stress conditions, corrosion resistance
 307 and slip resistance can vary (Pan et al., 2013). Based on the rainfall characteristics, rainfall
 308 patterns can be roughly divided into two kinds, the flat pattern and the peak pattern, as shown
 309 in Fig. 9. If the rainfall intensity has little variation, there is no obvious peak in the whole
 310 rainfall process; such rainfall can be described as flat pattern rainfall. If the soils characterized
 311 by low hydraulic conductivity, this kind of rainfall no longer time spans are relevant for mass
 312 movements. And the debris flows, if occur, are mainly caused by the great amount of effective
 313 antecedent precipitation. While if the rainfall intensity increases suddenly during a certain
 314 period of time, the rainfall process will have an obvious peak and is termed peak pattern rain-
 315 fall. If the hydraulic conductivity is high enough, the rainfall can totally enter the soil and
 316 mass can move easily. These debris flows are mainly controlled by the short-duration heavy
 317 rains. Peak pattern rainfall may have one peak or multi-peak (Pan, et al., 2013).



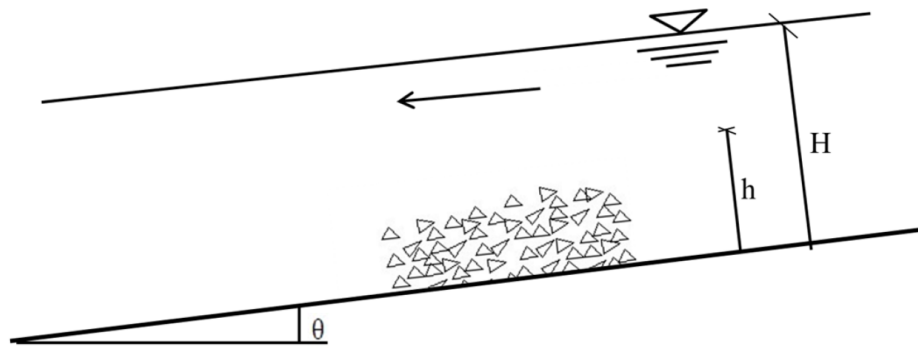
320 **Figure 9.** The diagram of rainfall patterns

321 Through analyzing the rainfall data of the Guojuanyan gully, the rainfall pattern and the
 322 spatial-temporal distribution characteristics can be obtained.

323 3.2 The rainfall threshold curve of debris flows

324 3.2.1 The initiation mechanism of hydraulic-driven debris flows

325 When the watershed hydrodynamics, which include the runoff, soil moisture content and
 326 the discharge, reach to a certain level, the loose deposits in the channel bed will initiate
 327 movement and the sediment concentration of the flow will increase, leading the sediment
 328 laden flow to transform into a debris flow. The formation of this kind of debris flow is a com-
 329 pletely hydrodynamic process. Therefore, it can be regarded as the initiation problem of de-
 330 bris flow under hydrodynamic force. The forming process of hydraulic-driven debris flows is
 331 shown in Fig. 10.



332
 333 **Figure 10.** The typical debris flow initiate model


334 According to Takahashi's model, the critical depth for hydraulic-driven debris flows is:

$$335 \quad h_0 = \left[\frac{C_* (\sigma - \rho) \tan \phi}{\rho \tan \theta} - \frac{C_* (\sigma - \rho)}{\rho} - 1 \right] d_m \quad (1)$$

336 where C_* is the volume concentration obtained by experiments(0.812); σ is the unit weight of
 337 loose deposits (usually is 2.65 g/cm³); ρ is the unit weight of water,1.0 g/cm³; θ is the longi-
 338 tudinal slope of the channel (°); ϕ is the internal friction angle (°) and can be measured by
 339 shear tests ; And d_m is the average grain diameter (mm), which can be expressed as:


$$340 \quad d_m = \frac{d_{16} + d_{50} + d_{84}}{3} \quad (2)$$

341 where d_{16} , d_{50} and d_{84} are characteristic particle sizes of the loose deposits (mm), whose
342 weight percentage are 16%, 50% and 84% separately.

343 Takahashi's model became one of the most common for the initiation of debris flow after
344 it was presented. A great deal of related studies was published based on Takahashi's model
345 later. Some  discussed the laws of debris flow according to the geomorphology and the water
346 content while others examined the critical conditions of debris flow with mechanical stability
347 analysis. However, Takahashi's relation was determined for debris flow propagating over a
348 rigid bed, hence, with a minor effect of quasi-static actions near the bed. Lanzoni et al. (2017)
349 slightly modified the Takahashi's formulation of the bulk concentration, which considered the
350 long-lasting grain interactions at the boundary between the upper, grain inertial layer and the
351 underlying static sediment bed, and validated the proposed formulation with a wide dataset of
352 experimental data (Takahashi, 1978, Tsubaki et al., 1983, Lanzoni, 1993, Armanini et al.,
353 2005). The effects of flow rheology on the basis of velocity profiles are analyzed with attention
354 to the role of different stress-generating mechanisms.

355 This study aims to the initiation of loose solid materials in the gully under surface runoff;
356 the interactions on the boundary are not involved. Therefore, Takahashi's model can be used
357 in this study.

358 **3.2.2 Calculation of watershed runoff yield and concentration**

359 The stored-full runoff, one of the modes of runoff production, is also called as the super
360 storage runoff. The reason of the runoff yield is that the aeration zone and the saturation zone
361 of the soil are saturated by rainfall. In the humid and semi humid areas where rainfall is
362 plentiful, because of the high groundwater level and soil moisture content, the loss of precipi-
363 tation is no longer increased with the rains continue, after meet plant interception and infil- 
364 tration, which produces a wide range of surface runoff. The Guojuanyan gully is located in Du
365 Jiangyan city, which is in a humid area. Therefore, stored-full runoff is the main pattern run-
366 off producing mechanism in this gully, and this runoff yield pattern is used to calculate the
367 watershed runoff. That is, it is supposed that the water storage can reach the maximum stor-
368 age capacity of the watershed after each heavy rain. It is common used in the humid and semi
369 humid areas in China to analyze the runoff yield mechanism. Therefore, the rainfall loss in

370 each time I is the difference between the maximum water storage capacity I_m and the soil
 371 moisture content before the rain P_a . Hence, the water balance equation of stored-full runoff is
 372 expressed as follows (Ye, et al., 1992):

$$373 \quad R = P - I = P - (I_m - P_a) \quad (3)$$

374 where R is the runoff depth (mm); P is the precipitation of one rainfall (mm); I is the rain-
 375 fall loss (mm); I_m is the watershed maximum storage capacity (mm) for a certain watershed,
 376 it is a constant for a certain watershed that can be calculated by the infiltration curve or infil-
 377 tration experiment data. In this study, I_m has been picked up from Handbook of rainstorm
 378 and flood in Sichuan (Sichuan Water and Power Department 1984); and P_a is the antecedent
 379 precipitation index, referring to the total rainfall prior to the 1-hour peak rainfall leading to
 380 debris flow initiation.

381 Eq. 5 can be expressed as follows:

$$382 \quad P + P_a = R + I_m \quad (4)$$

383 The precipitation intensity is a measure of the peak precipitation. At the same time, the
 384 duration of the peak precipitation is generally brief, lasting only up to tens of minutes. There-
 385 fore, 10-minute precipitation intensity (maximum precipitation over a 10-minute period dur-
 386 ing the rainfall event) is selected as the stimulating rainfall for debris flow, which is appropri-
 387 ate and most representative. However, it is difficult to obtain such short-duration rainfall data
 388 in areas with scarcity of data. Therefore, in this study, P and P_a are replaced by I_{60} (1 hour
 389 rainfall) and API (the antecedent precipitation index), respectively; thus, Eq. 6 is expressed
 390 as:

$$391 \quad I_{60} + API = R + I_m \quad (5)$$

392 In the hydrological study, the runoff depth R is:

$$393 \quad R = \frac{W}{1000F} = \frac{3.6 \sum Q \cdot \Delta t}{F} = \frac{3.6Q}{F} \quad (6)$$

394 where R is the runoff depth (m); W is the total volume of runoff (m³); F is the watershed area
 395 (km²); Δt is the duration time, in this study it is 1 hour; and Q is the average flow of the water-
 396 shed (m³/s), which can be expressed as follows:

$$397 \quad Q = BVh_0 \quad (7)$$

398 where B is the width of the channel (m), V is the average velocity (m/s) and h_0 is the critical
 399 depth (m).

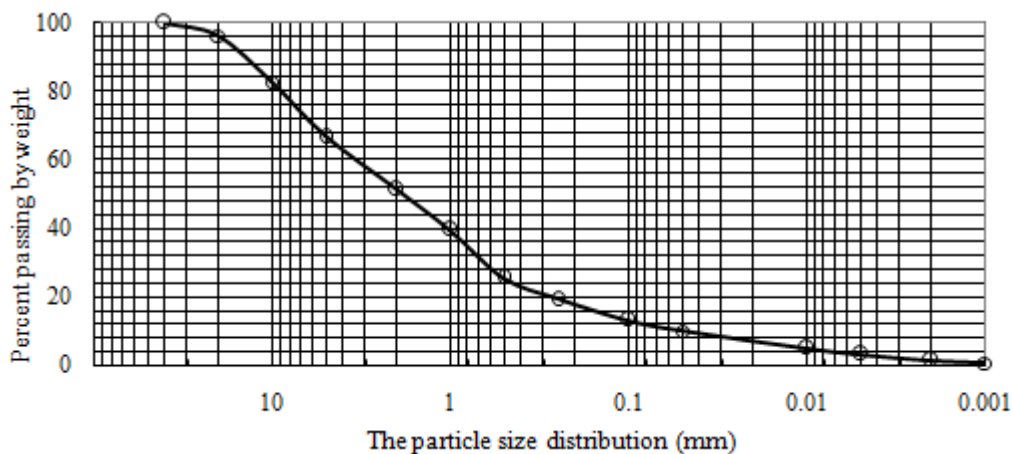
400 Eq. 5 is the expression of the rainfall threshold curve for a watershed, which can be used
 401 for debris flow early warning. This proposed rainfall threshold curve is a function of the ante-
 402 cedent precipitation index (API) and 1-hour rainfall (I_{60}), which is a line and a negative
 403 slope.

404 4 Results

405 4.1 The rainfall threshold curve of debris flow

406 4.1.1 The critical depth of the Guojuanyan gully

407 The grain grading graph (Fig. 11) is obtained by laboratory grain size analysis experi-
 408 ments for the loose deposits of the Guojuanyan gully. Figure 11 shows that the characteristic
 409 particle sizes d_{16} , d_{50} , d_{84} and d_m are 0.18 mm, 1.9 mm, and 10.2 mm, 4.1 mm, respective-
 410 ly. According to Eq. (1), the critical depth (h_0) of the Guojuanyan gully is 7.04 mm.



411
 412

Figure 11. The grain grading graph of the Guojuanyan gully

413 **Table 4.** Critical water depth of debris flow triggering in Guojuanyan gully

C_*	σ (g/cm ³)	ρ (g/cm ³)	θ (°)	$\tan \theta$	d_{16} (mm)	d_{50} (mm)	d_{84} (mm)	d_m (mm)	ϕ (°)	$\tan \phi$	h_0 (mm)
0.812	2.67	1.0	18.42	0.333	0.18	1.9	10.2	4.1	21.21	0.388	7.04

414 4.1.2 The rainfall threshold curve of debris flow

415 Taking the cross-section at the outlet of the debris flow formation region as the computa-
 416 tion object, based on the field investigations and measurements, the width of the cross-section
 417 is 20 m, and the average velocity of debris flows which is calculated by the several debris flow
 418 events, is 1.5m/s. Based on the Handbook of rainstorm and flood in Sichuan (Sichuan Water
 419 and Power Department 1984), the watershed maximum storage capacity (I_m) of the
 420 Guojuanyan gully is 100mm. According to Eq. (5) - Eq. (7), the calculated rainfall threshold
 421 curve of debris flow in the Guojuanyan gully is shown in Table 5.

422 **Table 5.** The calculated process of the rainfall threshold

Watershed	h_0 (mm)	B (m)	V (m/s)	Q (m ³ /s)	Δt (h)	F (km ²)	R (mm)	I_m (mm)	$R + I_m$ (mm)
Guojuanyan	7.04	20.0	1.5	0.197	1	0.11	6.9	100	106.9

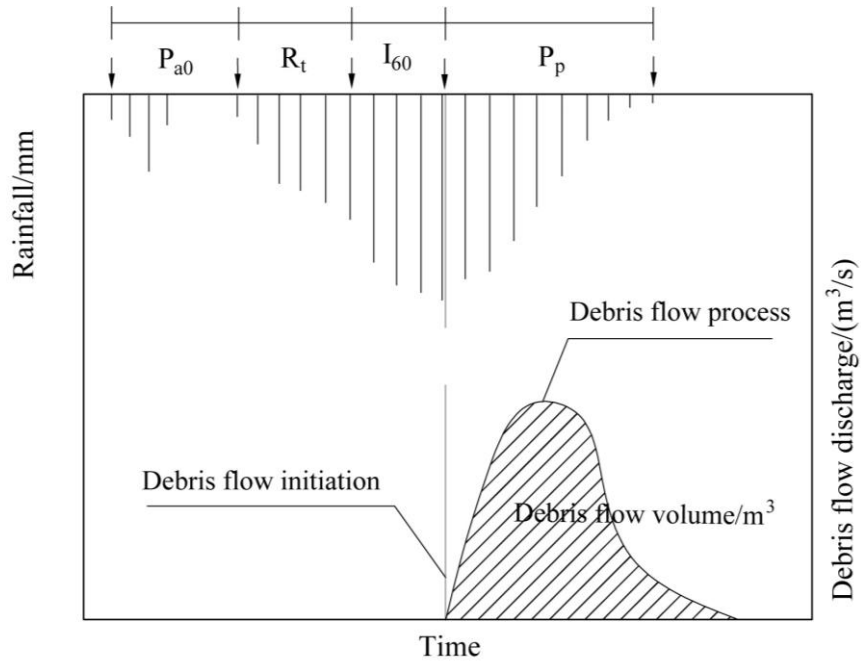
423 From the calculated results, we can conclude the rainfall threshold of the debris flow is
 424 $I_{60} + API = R + I_m = 106.9 \approx 107$ mm; that is, when the sum of the antecedent precipitation in-
 425 dex (API) and the 1 hour rainfall (I_{60}) reaches 107 mm (early warning area), the gully may
 426 trigger debris flow.

427 4.2 Validation of the results

428 4.2.1 The calculation of the antecedent precipitation index (API)

429 The rainfall factor influencing debris flows consists of three parts: indirect antecedent
 430 precipitation (IAP) (it is P_{a0} in this paper), direct antecedent precipitation (DAP) (it is R_t in this
 431 paper), and triggering precipitation (TP) (it is I_{60} in this paper). The relationships among them
 432 are shown in Figure 12. Obviously, IAP increases soil moisture and decreases the soil stability,
 433 and DAP saturates soils and thus decrease the critical condition of debris flow occurrence.
 434 Although TP is believed to initiate debris flows directly, its contribution amounts to only 37%
 435 of total water (Cui et al. 2007). Guo et al (2013) analyzed the rainstorms and debris flow
 436 events during June and September in 2006 and 2008, there were 208 days with antecedent
 437 rainfall more than 10mm, approximately 57% days of the rain season. Among them, there
 438 were 66 days with antecedent rainfall between 10-15mm, and 1 debris flow event happened;

439 53 days between 15-20 mm and 4 debris flow events happened; 28 days between 20-25 mm
 440 and 4 debris flow events happened; 30 days between 25-33 mm and 5 debris flow happened;
 441 and 35 days more than 33mm and 9 debris flow events happened. So, this group of data can
 442 specifically illustrate the importance of the antecedent rainfall to the debris flow events.



443
 444

Figure 12. Rainfall index classifications

445 As Fig. 12 shows, take 1-h rainfall (I_{60}) that obtained from the observed data of the
 446 Guojuanyan gully for the TP. The antecedent precipitation index (API) includes IAP and
 447 DAP, calculated as the following expression (Zhao, 2011; Guo, 2013; Zhuang, 2015):

$$448 \quad API = P_{a0} + R_t \quad (8)$$

449 where P_{a0} is the effective antecedent precipitation (mm) and R_t is the direct antecedent precip-
 450 itation (mm), which is the precipitation from the beginning of the rainfall that trigger debris
 451 flow to the 1 hour before the debris flow.

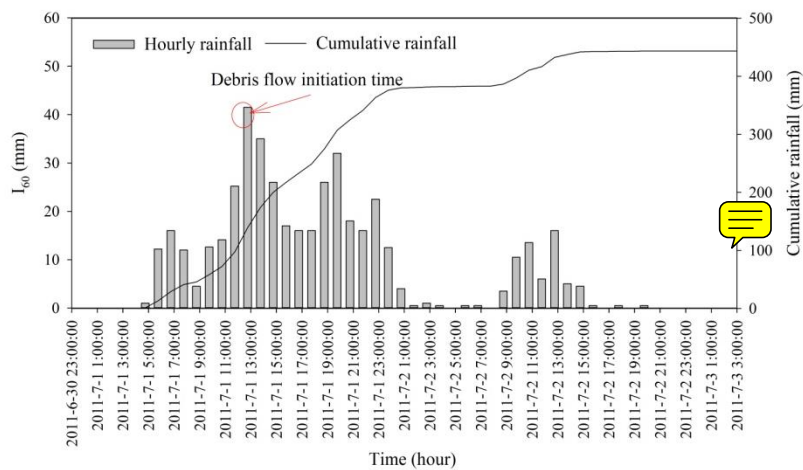
452 It's difficult to study the influence of antecedent rainfall to debris flow as it mainly relies
 453 on the heterogeneity of soils (strength and permeability properties), which makes it hard to
 454 measure the moisture. Usually, the frequently used method for calculating antecedent daily
 455 rainfall is the weighted sum equation as below (Crozier and Eyles 1980; Glade et al. 2000):

$$456 \quad P_{a0} = \sum_1^n P_i \cdot K_i \quad (9)$$

457 Where P_i is the daily precipitation in the i -th day proceeding to the debris flow event

458 $(1 \leq i \leq n)$ and K_i is a decay coefficient due to evaporation and geomorphological condi-
 459 tions of the soil. The value of the K can be determined by the test of soil moisture content
 460 based on Eq.9 in the watershed. The effect of a rainfall event usually diminishes with the time
 461 going forward. Different patterns of storm debris flow gullies require different numbers of
 462 previous indirect rainfall days, which can be determined by the relationship between the
 463 stimulating rainfall and the antecedent rainfall of a debris flow (Pan, et al., 2013). If the rain-
 464 fall is sharp and heavy, the initiation of debris flow would mainly be determined by DAP and
 465 TP, while the influence of the antecedent precipitation would be decreased, and vice versa.
 466 Generally, a typical rainstorm debris flow gully requires no more than 20 days of antecedent
 467 rainfall.

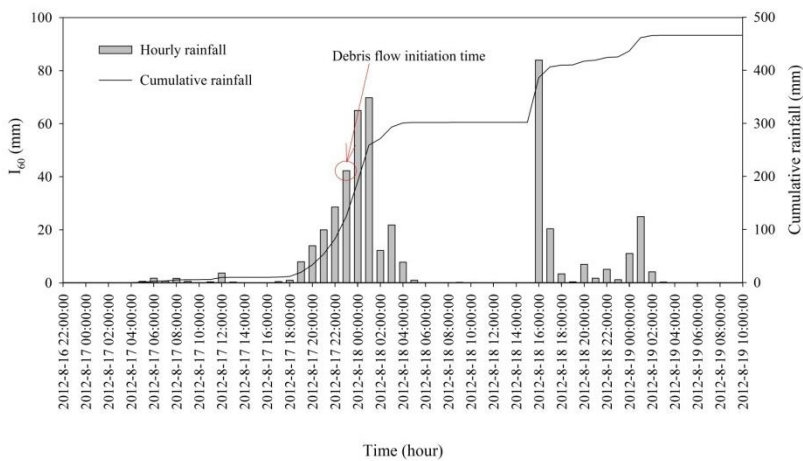
468 **4.2.2 The rainstorm and debris flow events in the Guojuanyan gully during**
 469 **2010-2014**



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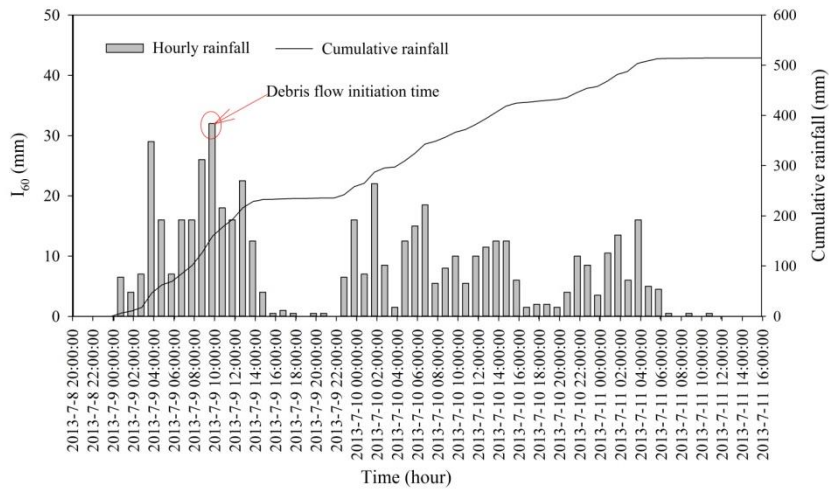
(a)



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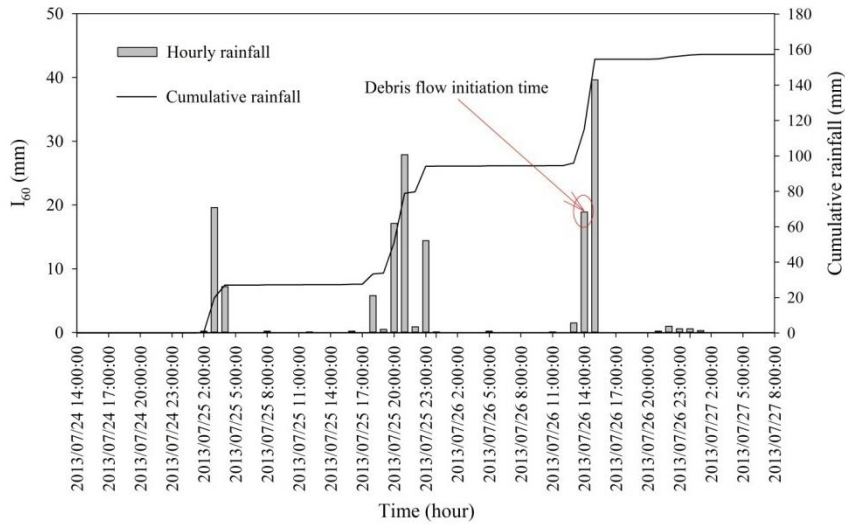
(b)



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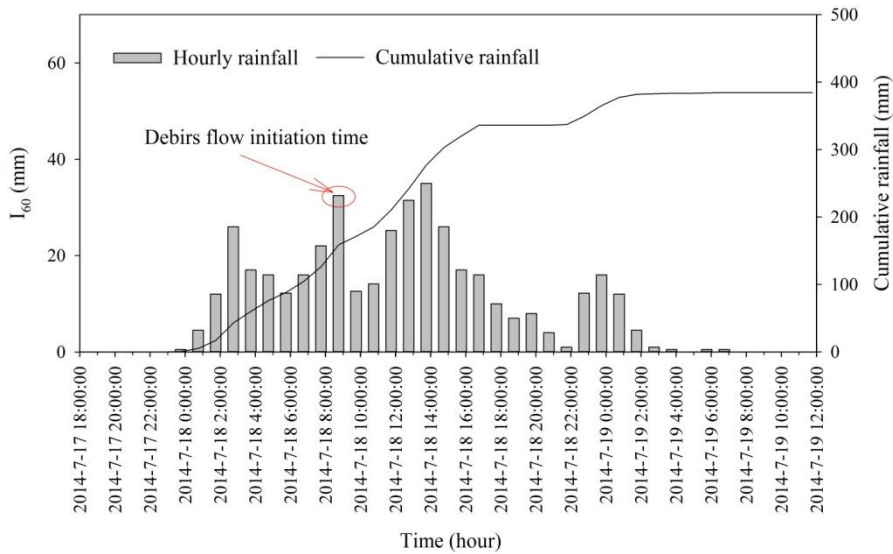
(c)



476

477

(d)



478

479

(e)

480 **Figure 13.** The rainfall process of debris flow vents in the Guojuanyan gully from 2011 to 2014 (a, July
481 1, 2011; b, August 17, 2012; c, July 9, 2013; d, July 26, 2013; e, July 18, 2014)

482 Table 3 shows that debris flows occurred almost every year after the earthquake. Based
483 on the field tests and experience, the value of K and n in Eq.9 are identified as 0.8 and 20
484 days separately (Cui et al. 2007). Thus, the duration and intensity of the 1-h triggering rain-
485 fall and cumulative rainfall for the typical rainstorms are shown in Table 6.

486 In addition to the rainfall process of the 5 debris flow events (Fig. 13), some typical rain-
487 falls whose daily rainfall were greater than 50 mm but did not trigger a debris flow were also
488 calculated; the greatest 1-h rainfall is considered as I_{60} (Table 6).

489 **Table 6.** The data of typical rainfall in the Guojuanyan gully after the earthquake

Time	Daily rainfall (mm)	Pa_0 (mm)	R_t (mm)	API (mm)	I_{60} (mm)	$API+I_{60}$ (mm)	Location to the threshold line	Triggered debris flow
1 July, 2011		9.7	97.6	107.3	41.5	148.8	Above	Yes
17 August , 2012		12.1	81.9	94.0	42.3	136.3	Above	Yes
9 July , 2013		5.7	127.5	133.2	32	165.2	Above	Yes
26 July , 2013		22.4	96.0	118.4	18.9	137.3	Above	Yes
18 July, 2014		10.7	116.2	126.9	32.5	159.4	Above	Yes
20 August , 2011	82.8	8.5	19.0	27.5	26.8	54.3	Below	No
5 September , 2011	52.1	48.7	1.2	49.9	16.2	66.1	Below	No
16 June , 2012	55.8	5.6	6.6	12.2	27.0	39.2	Below	No
3 August , 2012	148.3	7.5	84.3	91.8	26.7	118.5	Above	No
18 August , 2012	125.7	54.3	0	54.3	65.0	119.3	Above	No
18 June , 2013	50.6	6.2	3.8	10.0	40.0	50.0	Below	No
28 July , 2013	59.4	13.4	30.0	43.4	29.4	72.8	Below	No
6 August , 2013	56.1	12.4	34.0	46.4	17.1	63.5	Below	No

490

491 The proposed rainfall threshold curve is a function of the antecedent precipitation index
492 (API) and 1-h rainfall (I_{60}), which is a line and a negative slope. Fig. 14 shows that the calcu-
493 lated values $I_{60} + API$ of debris flow events in the Guojuanyan gully are all above the rainfall
494 threshold curve, while most of the rainstorms that did not trigger debris flow are lay below the
495 curve. That is, the proposed rainfall threshold curve is reasonable through the validation by
496 rainfall and hazards data of the Guojuanyan gully.

497

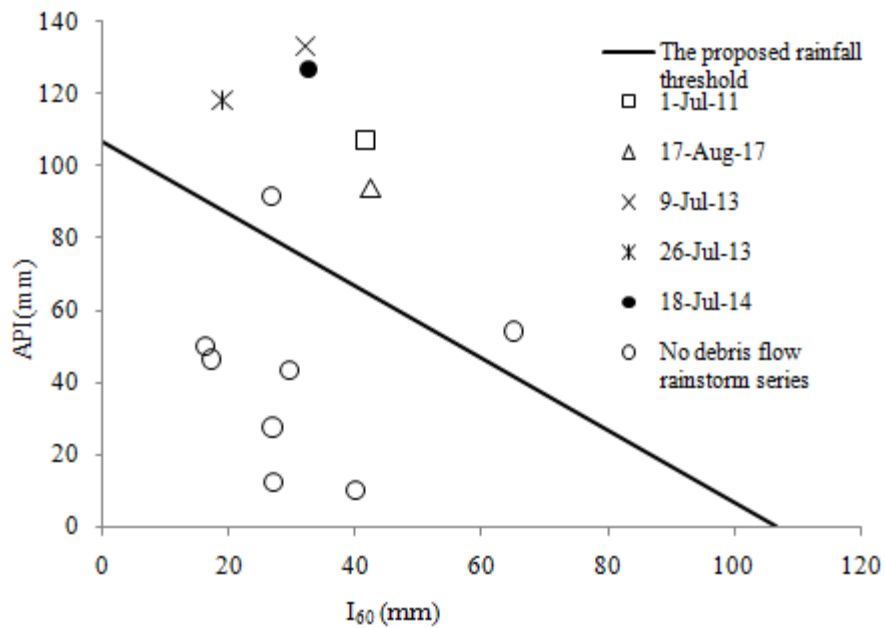


Figure 14. The proposed rainfall threshold curve of debris flow in the Guojuanyan gully

5 Discussions

5.1 About the two above points that did not trigger debris flows

The proposed rainfall threshold curve is a function of the antecedent precipitation index (API) and the 1-h rainfall (I_{60}), which has been validated by rainfall and hazards data and can be applied to debris flow early warning and mitigation. However, in Figure 14, there are two points above the curve that did not trigger debris flow at all. Although we have highlighted the significance and interconnect of antecedent rainfall, critical rainfall, 1 h triggering rainfall, as well as their accurate determination before the hour of debris flow triggering, it should be noticed that the rainfall is only the triggering factor of debris flows. A comprehensive warning system must contain more environmental factors, such as the geologic and geomorphologic factors, the distribution of source areas. The special and complex formative environment of debris flow after earthquake caused the rainfall threshold is much more complex and uncertain. The rainfall threshold of debris flow varies with the antecedent precipitation index (API), rainfall characteristics, amount of loose deposits, channel and slope characteristics, and so on. Therefore, we should further study the characteristics of the movable solid materials, the shape of gully, and so on to modify the rainfall threshold curve.

On the other hand, restricted by the limited rainfall data, this study was validated by only

517 5 debris flow events. Furthermore, as the initiation depth in distinct watershed is different
518 from each other because of the different topography and loose solid materials, hence the rain-
519 fall threshold is independent for each watershed. While most of debris flow gullies in Wen-
520 chuan earthquake affected areas with scarcity of rainfall data and disaster data, therefore, the
521 approach proposed in this study hasn't been validated by other gullies except the Guojuanyan
522 gully so far. Figure 13 and Figure 14 indicated that the only 5 debris flow events all triggered
523 by the rainfalls with high-intensity and short-duration. As mentioned before, the influence of
524 the antecedent rainfall in this kind of debris flow is relatively less. However, it still can't ignore
525 the significance role of the antecedent precipitation. Due to safety concerns, in the universali-
526 ty calculation of rainfall threshold for debris flow, it must fully consider the antecedent pre-
527 cipitation. Therefore, the days count for antecedent rainfall in this study is selected as 20. Of
528 course, the value of the curve should be further validated and continuously corrected with
529 more rainfall and disaster data in later years.

530 **5.2 Further studies about the debris flow early-warning in earthquake-hit** 531 **areas**

532 It should be noted that the methodological proposal of this study is based on the physical
533 process of debris flow initiation and involves modeling with physical characteristics of the
534 loose solid materials which served by the landslides triggered by earthquake; therefore, it's
535 suitable for the areas with scarcity of data especially the earthquake affected areas.

536 Actually, the times of debris flow events happened in the earthquake-hit areas were de-
537 creasing from 2014 on; there was even no debris flow event at all in Guojuanyan gully. Mainly
538 because of the unstable slopes as well as the materials are decreasing with the times go by.
539 Therefore, the rainfall threshold would increase accordingly. However, it may need a long
540 time, perhaps 15-20 years, according to the experiences in other earthquake-hit areas, such as
541 Chi-Chi earthquake, to recover to the normal value. Hence, the rainfall threshold is not a con-
542 stant value but changing with time.

543 **6 Conclusions**

544 (1) In the Wenchuan earthquake-stricken areas, loose deposits are widely distributed,

545 causing dramatic changes on the environmental development for the occurrence of debris
546 flow; thus, the debris flow occurrence increased dramatically in the subsequent years. The
547 characteristics of the 10-min, 1-h and 24-h critical rainfalls were represented based on a com-
548 prehensive analysis of limited rainfall and hazards data. The statistical results show that the
549 10-min and 1-h critical rainfalls of different debris flow events have minor differences; how-
550 ever, the 24 hour critical rainfalls vary widely. The 10-min and 1-h critical rainfalls have a no-
551 tably higher correlation with debris flow occurrences than to the 24-h critical rainfalls.

552 (2) The rainfall pattern of the Guojuanyan gully is the peak pattern, both single peak and
553 multi-peak. The antecedent precipitation index (API) was fully explored by the antecedent
554 effective rainfall and stimulating rainfall.

555 (3) As an important and effective means of debris flow early warning and mitigation, the
556 rainfall threshold of debris flow was determined in this paper, and a new method to calculate
557 the rainfall threshold is put forward. Firstly, the rainfall characteristics, hydrological charac-
558 teristics, and some other topography conditions were analysed. Then, the critical water depth
559 for the initiation of debris flows is calculated according to the topography conditions and
560 physical characteristics of the loose solid materials. Finally, according to the initiation mecha-
561 nism of hydraulic-driven debris flow, combined with the runoff yield and concentration laws
562 of the watershed, this study promoted a new method to calculate the debris flow rainfall
563 threshold. At last, the hydrological condition for the initiation of a debris flow is the result of
564 both short-duration heavy rains (I_{60}) and the antecedent precipitation index (API). The
565 proposed approach resolves the problem of debris flow early warning in areas with scarcity
566 data, can be used to establish warning systems of debris flows for similar catchments in areas
567 with scarcity data although it still need further modification. This study provides a new
568 thinking for the debris flow early warning in the mountain areas.

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